

The scattering polarization of the $\text{Ly}\alpha$ lines of H I and He II taking into account PRD and J -state interference effects

LUCA BELLUZZI^{1,2}, JAVIER TRUJILLO BUENO^{1,2,3}, AND JIŘÍ ŠTĚPÁN⁴

ABSTRACT

Recent theoretical investigations have pointed out that the cores of the $\text{Ly}\alpha$ lines of H I and He II should show measurable scattering polarization signals when observing the solar disk, and that the magnetic sensitivity, through the Hanle effect, of such linear polarization signals is suitable for exploring the magnetism of the solar transition region. Such investigations were carried out in the limit of complete frequency redistribution (CRD) and neglecting quantum interference between the two upper J -levels of each line. Here we relax both approximations and show that the joint action of partial frequency redistribution (PRD) and J -state interference produces much more complex fractional linear polarization (Q/I) profiles, with large amplitudes in their wings. Such wing polarization signals turn out to be very sensitive to the temperature structure of the atmospheric model, so that they can be exploited for constraining the thermal properties of the solar chromosphere. Finally, we show that the approximation of CRD without J -state interference is however suitable for estimating the amplitude of the linear polarization signals in the core of the lines, where the Hanle effect operates.

Subject headings: polarization — scattering — radiative transfer — Sun: chromosphere — Sun: transition region — Sun: surface magnetism

1. Introduction

In the transition region between the chromosphere and corona of the Sun, the kinetic temperature suddenly jumps from 10^4 K to 10^6 K and the plasma changes from partially to practically fully

¹Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain

²Departamento de Astrofísica, Facultad de Física, Universidad de La Laguna, Tenerife, Spain

³Consejo Superior de Investigaciones Científicas, Spain

⁴Astronomical Institute ASCR, Ondřejov, Czech Republic

ionized. Although various physical mechanisms have been proposed for explaining this temperature increase, the lack of reliable measurements of key physical quantities, such as the magnetic field, represents today the most serious limitation to a better comprehension of the role played by this boundary region on the heating of the solar corona. In order to make measurements of the quantities that remain basically unknown, we need (1) to identify observables sensitive to the physical conditions of the solar transition region, (2) to develop the instruments needed for measuring such observables, and (3) to infer the relevant physical quantities (e.g., the strength and orientation of the magnetic field) through realistic modeling of the measured observables.

Recently, Trujillo Bueno et al. (2011) argued that the hydrogen Ly α line at 1216 Å should show measurable scattering polarization signals when observing the solar disk, and that via the Hanle effect the line-center amplitudes of the Q/I and U/I linear polarization profiles must be sensitive to the strength and orientation of the magnetic field in the solar transition region (with good sensitivity to magnetic field strengths between 10 and 100 G). In a subsequent paper, Trujillo Bueno et al. (2012) pointed out that significant line-center scattering polarization signals are to be expected also for the Ly α line of He II at 304 Å, and that for the magnetic field strengths expected at transition region heights (i.e., $B \lesssim 100$ G outside active regions) the He II 304 Å line, due to its very large Einstein coefficient, is immune to the Hanle effect (i.e., it is a line whose observed linear polarization pattern could be used as a reference for facilitating the identification of the observational signature of the Hanle effect in the hydrogen Ly α line). The possibility that scattering processes produce measurable linear polarization signals in these and other emission lines of the solar transition region is of great scientific interest, because it is mainly through the Hanle effect that we may hope to explore the magnetism of the upper chromosphere and transition region of the Sun. As a matter of fact, with few exceptions, the polarization signals induced by the Zeeman effect in transition region lines are expected to be very weak (e.g., in typical semi-empirical models of the solar atmosphere a volume-filling magnetic field of 100 G inclined by 45° with respect to the line of sight (LOS) produces in both Ly α lines circular polarization V/I signals significantly smaller than 0.1%, while the contribution of the transverse Zeeman effect to their linear polarization is insignificant).

The conclusions of Trujillo Bueno et al. (2011, 2012) were obtained through detailed radiative transfer (RT) calculations in semi-empirical and hydrodynamical models of the solar atmosphere, applying the quantum theory of polarization described in the monograph by Landi Degl’Innocenti & Landolfi (2004). This density-matrix theory is based on the approximation of complete frequency redistribution (CRD), which neglects correlations between the frequencies of the incoming and outgoing photons in the scattering events. In addition, Trujillo Bueno et al. (2011, 2012) neglected quantum interference between the $^2P_{1/2}$ and $^2P_{3/2}$ upper levels of such Ly α lines. Both approximations should be suitable for estimating the linear polarization amplitudes at the line center, which is where the Hanle effect operates. However, in strong resonance lines the joint action of partial frequency redistribution (PRD) and J -state interference can produce important observational sig-

natures in the wings of the fractional linear polarization (Q/I) profiles (e.g., Smitha et al. 2011a,b; Belluzzi & Trujillo Bueno 2012).

The aim of the present paper is to investigate the impact of PRD and J -state interference effects on the scattering polarization of the $\text{Ly}\alpha$ lines of H I and He II. To this end, we apply the same theoretical framework and RT code that Belluzzi & Trujillo Bueno (2012) developed for investigating the scattering polarization pattern across the h and k lines of Mg II. Like the Mg II h and k lines, also the above-mentioned $\text{Ly}\alpha$ lines result from two transitions between a common lower level with angular momentum $J = 1/2$ and two upper levels with $J = 1/2$ and $J = 3/2$. However, in contrast with the case of the Mg II resonance lines, the two components of each $\text{Ly}\alpha$ line are fully blended since the fine-structure splitting between the two upper J -levels is much smaller than the Doppler line width.¹

2. Formulation of the problem

This investigation has been carried out within the same theoretical framework that has been recently developed by Belluzzi & Trujillo Bueno (2012) for investigating the polarization properties of the Mg II h and k lines. The reader is referred to that paper for more details on the theoretical tools that we have applied.

We consider a *two-term* atomic model both for H I and He II, the lower term being composed of the ground level ($^2\text{S}_{1/2}$) and the upper term of the upper levels ($^2\text{P}_{1/2}$ and $^2\text{P}_{3/2}$). Such atomic model allows us to take into account the fine structure of the $\text{Ly}\alpha$ line, as well as the contribution of the J -state interference between the two upper J -levels.

The Non-LTE RT problem is formulated within the redistribution matrix formalism. We consider a linear combination of the R_{II} and R_{III} redistribution matrices (which describe purely coherent scattering and completely redistributed scattering in the atom rest frame, respectively), for a two-term atom with unpolarized and infinitely sharp lower term, in the absence of magnetic fields. The redistribution matrix R_{II} in the observer frame is calculated starting from the expression derived by Landi Degl’Innocenti et al. (1997) in the atom rest frame, and taking Doppler redistribution into account (see Eq. (3) of Belluzzi & Trujillo Bueno 2012). The redistribution matrix R_{III} is calculated in the limit of complete frequency redistribution (CRD) in the observer frame, starting from the CRD theory for a two-term atom presented in Landi Degl’Innocenti & Landolfi (2004). The effect of inelastic and superelastic collisions is included under the same approximations made in

¹Note that the fine-structure splitting between the two upper J -levels, though small, is in any case much larger than the levels natural width.

Belluzzi & Trujillo Bueno (2012). The collisional rates for the H I Ly α line have been calculated from Przybilla & Butler (2004), those for the He II Ly α line from Janev et al. (1987).

We consider the branching ratios for R_{II} and R_{III} derived for the two-level atom case (see Bommier 1997a,b). Neglecting depolarizing collisions, such branching ratios are given by α and $(1 - \alpha)$, respectively, with²

$$\alpha = \frac{\Gamma_R + \Gamma_I}{\Gamma_R + \Gamma_I + \Gamma_E}. \quad (1)$$

The quantities Γ_R , Γ_I , and Γ_E are the broadening widths of the upper level due to radiative decays, superelastic collisions, and elastic collisions, respectively.³

The variation of α as a function of height for the two lines under investigation, in the semi-empirical solar atmosphere model C of Fontenla et al. (1993) (hereafter, FAL-C), is shown in the left panel of Fig. 1. As pointed out in Trujillo Bueno et al. (2012), and as it can be seen from the right panel of Fig. 1, the He II Ly α line forms in a thin layer of the transition region (approximately, between about 2000 and 2200 km). As shown in the left panel of Fig. 1, at these heights α is essentially equal to unity so that the assumption of purely coherent scattering in the atom rest frame is an excellent approximation for the modeling of this line. The situation is slightly different as far as the H I Ly α line is concerned. While the core of this line forms in the transition region, just a few kilometers below the core of the He II Ly α line, its broad wings form deeper in the chromosphere, where α assumes values appreciably smaller than one, though larger than 0.9. The approximation of purely coherent scattering in the atom rest frame is thus not so good for this line, and its modeling requires to take both R_{II} and R_{III} into account.

The polarization profiles of the two lines under investigation are calculated by applying a Non-LTE RT code based on the angle-averaged expressions of R_{II} and R_{III} , and including the contribution of an unpolarized continuum. The numerical method of solution is a direct generalization to the PRD case of the Jacobian iterative scheme presented in Trujillo Bueno & Manso Sainz (1999). The initialization of the iterative calculation is done using the self-consistent solution of the corresponding unpolarized problem, obtained by applying Uitenbroek’s (2001) RT code. The same code is used to calculate the continuum opacity (including the UV line haze) and emissivity.

We point out that due to the negligible impact of J -state interference on Stokes- I , the PRD intensity $I(\lambda)$ profiles obtained with our code coincide with those computed using Uitenbroek’s (2001) code (which neglects J -state interference). As we shall see below, J -state interference

²Note that the branching ratios α and $(1 - \alpha)$, defined according to Eq. (1), do not include the factor $(1 - \epsilon)$, with ϵ the photon destruction probability. This factor is directly included in the redistribution matrices.

³Our theoretical formulation is based on the hypothesis that such broadening widths are identical for the two levels of the upper term. This is a very good approximation for the model atoms considered in this work.

effects, together with those caused by PRD, have however an important impact on the Q/I profiles.

3. The scattering polarization profile of the H I Ly α line at 1216 Å

Figure 2 shows the PRD Q/I profiles of the H I Ly α line, obtained by taking into account and neglecting quantum interference between the two upper J -levels. The calculations have been performed in the FAL-C atmospheric model, for a line-of-sight (LOS) with $\mu \equiv \cos \theta = 0.3$ (with θ the heliocentric angle).

The two profiles perfectly coincide in the core of the line where J -state interference does not produce any observable signature (cf., Belluzzi & Trujillo Bueno 2011). In this spectral region, our PRD profile shows a good agreement with the corresponding CRD profile calculated by Trujillo Bueno et al. (2011) (see the left panel of their Fig. 2).⁴

Outside the line core, PRD effects produce a complex linear polarization profile with extended wings, while J -state interference plays a significant role, producing much larger polarization amplitudes with respect to the case in which it is neglected. The profile obtained by taking J -state interference into account shows in particular two narrow negative peaks at approximately ± 0.4 Å from line center, with an amplitude of about -7%, and two broad negative lobes with a minimum of about -6% at approximately ± 10 Å from line center. As seen in Fig. 3, the shape of the Q/I profile remains qualitatively the same for line of sights corresponding to larger μ values, although the Q/I amplitudes are clearly smaller.

Figure 4 shows the sensitivity of the scattering polarization profile of the hydrogen Ly α line to the thermal structure of the model atmosphere. We compare the results for the atmospheric models C, F and P of Fontenla et al. (1993), which can be considered as illustrative of quiet, network and plage regions. Such sensitivity is due to the fact that the anisotropy of the incident radiation field (which induces atomic level polarization in the $^2P_{3/2}$ level and quantum interference between its sublevels and those of the $^2P_{1/2}$ level) depends on the gradient of the Stokes- I component of the source function (e.g., Trujillo Bueno 2001; Landi Degl’Innocenti & Landolfi 2004). Notice that especially the wing Q/I signals, which are insensitive to the magnetic field (since the Hanle effect operates only in the line core), are very sensitive to the temperature structure of the model atmosphere. Therefore, in addition to the $I(\lambda)$ profile itself, the wings of the Q/I profile could help us to constrain the thermal properties of the observed atmospheric region, and this would in turn facilitate the modeling of the line-core signals and the inference of the magnetic field.

⁴We point out that our PRD calculations and the CRD calculations of Trujillo Bueno et al. (2011) were made fixing the total neutral hydrogen number density to the values tabulated in the FAL-C model.

4. The scattering polarization profile of the He II Ly α line at 304 Å

The left panel of Fig. 5 shows our PRD results for the Q/I profile of the Ly α line of He II calculated in the FAL-C atmospheric model, taking into account (solid line) and neglecting (dashed line) the impact of J -state interference. The line-core polarization, and its modification by the Hanle effect, can be safely modeled in the CRD limit, and neglecting J -state interference. However, as soon as we go outside the line-core region, the combined action of PRD and J -state interference effects produces strong Q/I signals, which are not obtained when such physical ingredients are neglected. The right panel of Fig. 3 shows the center to limb variation of the Q/I profile.

Finally, in the right panel of Fig. 5 we provide information on the sensitivity of the Q/I profile to the thermal structure of the atmospheric model. As can be seen, the wings of the Q/I signals are very sensitive to the model’s temperature structure, while the line-core signals are practically identical in the three atmospheric models.

5. Understanding the impact of J -state interference

The impact of J -state interference on the Q/I profiles of various multiplets was first demonstrated and explained in Stenflo (1980) and considered in greater detail in Stenflo (1997), Landi Degl’Innocenti & Landolfi (2004), and Belluzzi & Trujillo Bueno (2011).

The results presented in the previous sections show that in the wings of the lines, the amplitude of the Q/I profiles is about a factor 3 larger when the effects of J -state interference are taken into account (see Figs. 2 and 5). In order to understand this behavior, we first note that far away from its “center of gravity”, a multiplet (in which the contribution of interference between different J -levels is taken into account) behaves in resonance scattering as a two-level atom transition with $J_\ell = L_\ell$ and $J_u = L_u$ (see Landi Degl’Innocenti & Landolfi 2004). We also observe that at these frequencies scattering is purely coherent in the observer frame. Starting from the expressions of the emission coefficients given in Landi Degl’Innocenti et al. (1997), it can be shown that, far from the center of gravity of the multiplet, the fractional polarization of the radiation scattered at 90° is given by

$$[p_Q(\nu)]_{\text{int.}} \equiv \frac{\varepsilon_Q(\nu)}{\varepsilon_I(\nu)} = \frac{3}{4} W_2(L_\ell, L_u) w(\nu) , \quad (2)$$

where the quantity $W_2(J_\ell, J_u)$ is defined in Eq. (10.17) of Landi Degl’Innocenti & Landolfi (2004), $w(\nu) = \sqrt{2}J_0^2(\nu)/J_0^0(\nu)$ is the monochromatic anisotropy factor, and where we have neglected the contribution of J_0^2 to ε_I (see Eq. (5.157) of Landi Degl’Innocenti & Landolfi 2004, for the definition of the radiation field tensor $J_Q^K(\nu)$).

From the same equations, it can be shown that for a multiplet having a single J -level in the

lower term, far from its center of gravity, the fractional polarization obtained taking into account the contribution of the various lines, but neglecting interference, is given by

$$[p_Q(\nu)]_{\text{no int.}} = \sum_{J_u} S_{J_u} \frac{3}{4} W_2(J_\ell, J_u) w(\nu), \quad (3)$$

where S_{J_u} is the relative strength of the $J_\ell \rightarrow J_u$ transition (see, e.g., Eq. (3.65) of Landi Degl’Innocenti & Landolfi 2004). For our $^2S - ^2P$ multiplet, having $L_\ell = 0$ and $L_u = 1$, we then have

$$\frac{[p_Q(\nu)]_{\text{int.}}}{[p_Q(\nu)]_{\text{no int.}}} = \frac{W_2(1, 0)}{S_{1/2} W_2(1/2, 1/2) + S_{3/2} W_2(1/2, 3/2)}. \quad (4)$$

Using the numerical values $W_2(1, 0) = 1$, $W_2(1/2, 1/2) = 0$, $W_2(1/2, 3/2) = 1/2$, $S_{1/2} = 1/3$, $S_{3/2} = 2/3$, we easily find $[p_Q(\nu)]_{\text{int.}} / [p_Q(\nu)]_{\text{no int.}} = 3$, in agreement with the numerical results shown in this Letter.

6. Conclusions

As shown in this Letter, the joint action of PRD and J -state interference effects produce complex scattering polarization Q/I profiles in the $\text{Ly}\alpha$ lines of H I and He II, with large polarization amplitudes in the wings. PRD effects determine the qualitative shape of the Q/I profiles, while J -state interference plays a key role in producing the large polarization amplitudes in the wings of the lines. Such wing polarization signals turn out to be very sensitive to the temperature structure of the atmospheric model. They could thus be exploited, in addition to the intensity profile itself, to constrain the thermal properties of the solar chromosphere.

As expected, the CRD approximation is only suitable for estimating the line-core signals. For instance, for a LOS with $\mu = 0.3$ the line-center Q/I signal of the He II 304 Å line calculated with PRD and J -state interference in the FAL-C atmospheric model is about -1.3% , while it is about a factor three smaller for the hydrogen $\text{Ly}\alpha$ line. These line-center Q/I amplitudes are in good agreement with those obtained by Trujillo Bueno et al. (2012), who assumed CRD and neglected J -state interference effects for investigating the impact of the Hanle effect on the linear polarization produced by scattering processes in the core of such $\text{Ly}\alpha$ lines.

Finally, it is of interest to estimate how large are the linear polarization amplitudes that result from the wavelength-integrated Stokes profiles ($\langle Q \rangle / \langle I \rangle$). It turns out that for the He II line $\langle Q \rangle / \langle I \rangle$ is similar to the line-center amplitude (e.g., for a LOS with $\mu = 0.3$ we have $\langle Q \rangle / \langle I \rangle \approx -1.3\%$ in the FAL-C model), while for the hydrogen $\text{Ly}\alpha$ line $\langle Q \rangle / \langle I \rangle$ is much larger than the line-center amplitude (e.g., for a LOS with $\mu = 0.3$ we have $\langle Q \rangle / \langle I \rangle \approx -3\%$ in the FAL-C model). Narrow band filter polarimetry (e.g., with a FWHM ~ 1 Å) in these $\text{Ly}\alpha$ lines would provide interesting I , Q/I

and U/I images over a large field of view. However, the information on the magnetic field of the solar transition region is encoded in the line-core polarization of the hydrogen $\text{Ly}\alpha$ line, which is where the Hanle effect operates. For this reason, the Chromospheric $\text{Ly}\alpha$ Spectropolarimeter (see Kobayashi et al. 2012) aims at doing spectropolarimetry of the hydrogen $\text{Ly}\alpha$ line with a spectral resolution of 0.1 \AA and a polarimetric sensitivity of 0.1% . Since outside active regions the He II 304 \AA line (which originates entirely within the transition region) is practically immune to the Hanle effect, the possibility of having in addition the information provided by filter polarimetry in this reference line would facilitate the diagnostics of the thermal and magnetic structure of the solar transition region.

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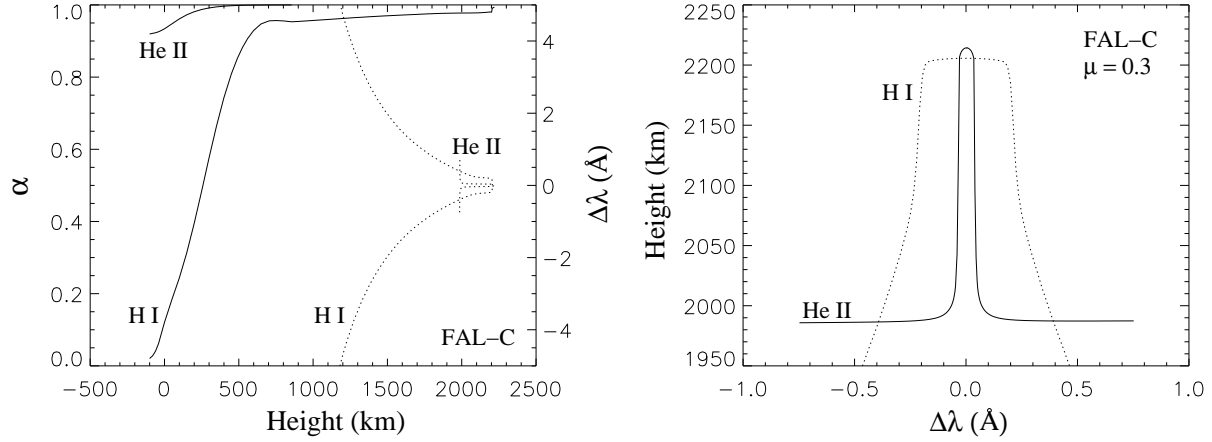


Fig. 1.— Left panel: the solid lines show, for each Ly α line, the variation with height in the FAL-C model atmosphere of the branching ratio α of Eq. (1). Note that for the He II 304 Å line α is essentially equal to unity at chromospheric and transition region heights. The corresponding dotted lines give the atmospheric height where, at each wavelength, the ensuing optical depth is unity along a LOS with $\mu = 0.3$ (see also the right panel for a magnified visualization).

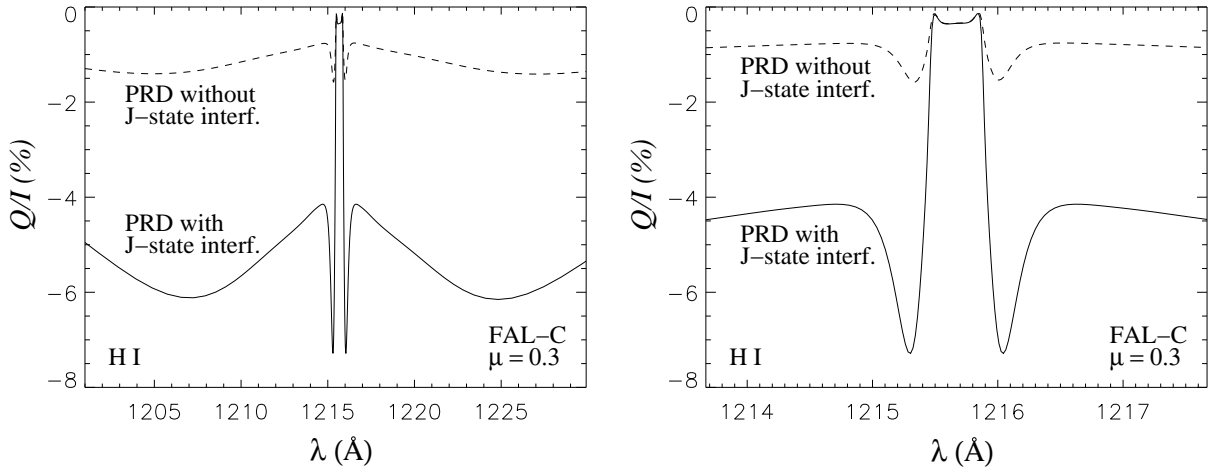


Fig. 2.— The PRD Q/I profile across the hydrogen Ly α line, calculated in the FAL-C model atmosphere for a LOS with $\mu = 0.3$, taking into account (solid line) and neglecting (dashed line) J -state interference. The right panel shows in more detail the line core region. The reference direction for positive Q is the parallel to the nearest limb.

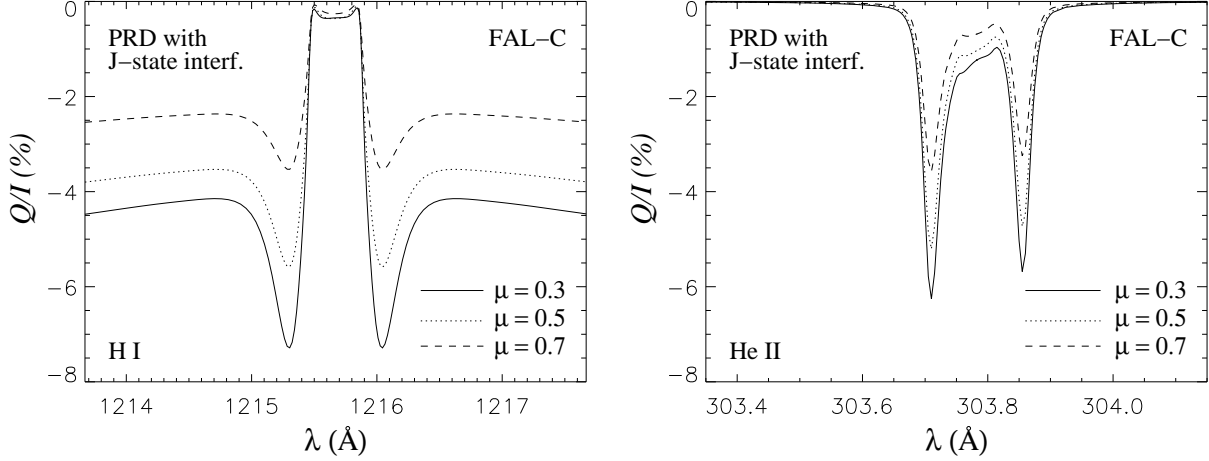


Fig. 3.— The center to limb variation of the Q/I profile of the $\text{Ly}\alpha$ lines of H I (left panel) and He II (right panel), calculated in the FAL-C model atmosphere. The reference direction for positive Q is the parallel to the nearest limb.

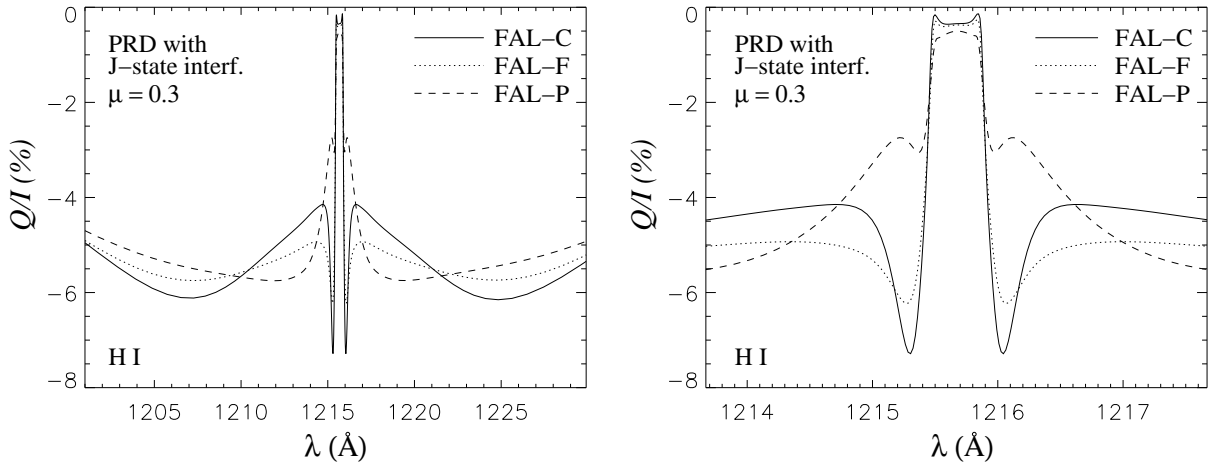


Fig. 4.— The Q/I profile of the hydrogen $\text{Ly}\alpha$ line calculated in the indicated atmospheric models, taking into account PRD and J -state interference effects. The right panel shows in more detail the line core region. The reference direction for positive Q is the parallel to the nearest limb.

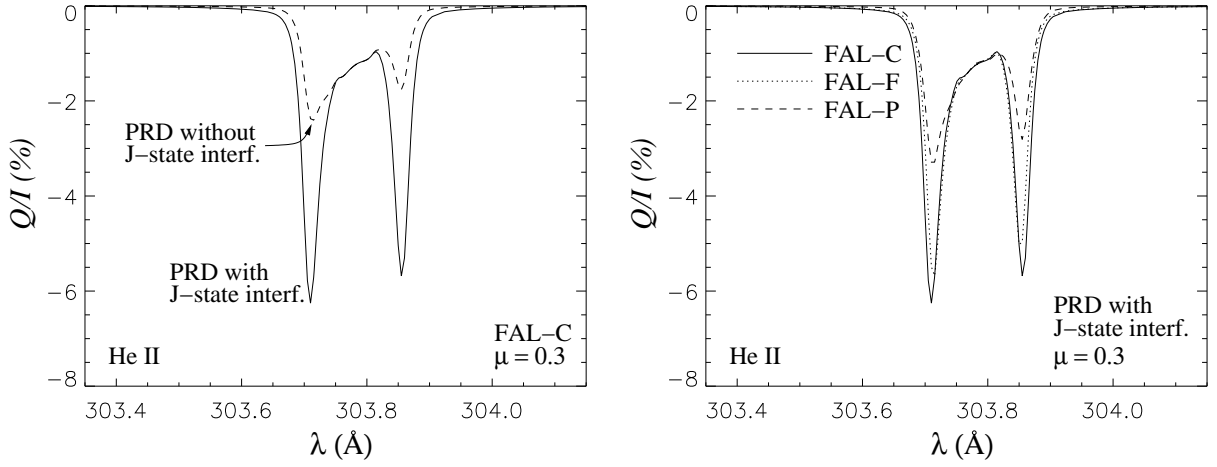


Fig. 5.— Left panel: the PRD Q/I profile across the He II Ly α line, calculated in the FAL-C model atmosphere for a LOS with $\mu = 0.3$, taking into account (solid line) and neglecting (dashed line) J -state interference. Right panel: the Q/I profile calculated in the indicated atmospheric models, taking into account PRD and J -state interference effects. The reference direction for positive Q is the parallel to the nearest limb.